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This presentation does not contain any proprietary or sensitive information
AVTA Background and Goals

• The Advanced Vehicle Testing Activity (AVTA) is part of DOE’s Vehicle Technology Program

• The Idaho National Laboratory (INL) conducts the AVTA for DOE, with Electric Transportation Engineering Corporation (ETEC) providing testing support. Argonne National Laboratory conducts the dynamometer testing

• The AVTA goals:
  – Provide benchmark data to technology modelers, research and development programs, vehicle manufacturers (via VSATT), and target and goal setters
  – Assist fleet managers in making informed early adopter vehicle purchase, deployment and operating decisions
AVTA Testing by Technology

- **Plug-in hybrid electric vehicles (PHEV)**
  - 12 models, 187 vehicles, 1,000,000 fleet test miles
- **Hybrid electric vehicles (HEV)**
  - 17 models, 45 vehicles, 5.5 million test miles
- **Neighborhood electric vehicles**
  - 23 models, 200,000 test miles
- **Hydrogen ICE (internal combustion engine) vehicles**
  - 7 models, 400,000 test miles
- **Full-size battery electric vehicles (BEVs)**
  - 40 BEV models, 5+ million test miles
- **Urban electric vehicles**
  - 3 models, 1 million test miles
12 PHEVs Models in Testing/Demonstrations

- Hymotion Prius (A123Systems)
- Hymotion Escape (A123Systems)
- Ford E85 Escape (Johnson Controls/Saft)
- EnergyCS Prius, 2 models (Valance and Altair Nano)
- Electrovaya Escape (Electrovaya)
- Hybrids Plus Escape, 2 models (Hybrids Plus and K2 Energy Solutions)
- Hybrids Plus Prius (Hybrids Plus)
- Manzanita Prius (lead acid)
- Manzanita Prius (Thunder Sky)
- Renault Kangoo (Saft NiCad)
- (All batteries are Lithium unless noted)
PHEV Testing Methods and Objectives

• Perform independent testing of PHEVs, using:
  – Baseline performance testing: closed test tracks and dynamometers
  – Accelerated testing: dedicated drivers operating on defined onroad loops
  – Fleet testing: everyday unstructured \ non-directed fleet and public use, with onboard data loggers
  – Laboratory testing of PHEV batteries

• Testing used to document:
  – Battery life, charging patterns and profiles
  – Vehicle operations, fuel use (electricity and gasoline) and infrastructure requirements
  – Driver influences on fuel use
  – Individual PHEV models and PHEV concepts
Fleet Demonstration Partners

- 75+ Testing partners in the U.S. and Canada, including:
  - 40 Electric utilities and 2 clean air agencies
  - 10 City, county, state, and province governments
  - 7 Private companies and advocacy organizations
  - 8 Universities and colleges
  - 2 PHEV conversion companies
  - 1 sea port and 1 DOD facility

- Operating in
  - 22 U.S. states
  - 4 Canadian provinces
PHEVs and Demonstration Locations

30 + 18 = 48 in Canada

11 + 1 = 2

25

10 + 15 = 25

179 Operating

12 Out of Service

227 Total

36 Coming ‘09

1 in DC
PHEV Fleet Testing Reports

- Summary reports posted monthly on web
- Individual vehicle reports only go to the respective fleets each month, 950+ reports to date (July 1, 2009)
- 150 Hymotion Prius PHEVs, 710,000 miles, 76,000 trips, 18,000 charging events, 43,000 kWh used. V2Green and Kvaser data logger reports
Hymotion Prius (V2Green Logger) Fleet Tests

- March 01/08 to July 01/09. 110 PHEVs, 498,000 miles, 54,000 trips, 12,400 charging events and 31,000 kWh used.
Hymotion Prius PHEV

- Conversion PHEV based on Gen II Toyota Prius
- 5 kWh additional battery system installed in rear of vehicle
  - Production NiMH battery is continued to be used
- Power is transferred from the Hymotion Li-Ion batteries to the vehicle through a DC/DC converter
  - Energy transfer is uni-directional
    - Hymotion system is not recharged by regen braking nor engine power
    - Grid energy recharges battery system through on-board charger
Ambient Temperature Significantly Impacts Fuel Economy of PHEV’s

Hymotion Prius Fleet Fuel Economy

- All Trips
- CD
- CD/CS
- CS

Average Ambient Temperature [°C]

Average Fuel Economy [MPG]

- <20°C
- -20°C to -10°C
- -10°C to 0°C
- 0°C to 10°C
- 10°C to 20°C
- 20°C to 30°C
- 30°C to 40°C
- >40°C

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
Reasons for Decreased PHEV Fuel Economy at Extreme Temperatures

• IC Engine
  – Increased operating time at low temperatures
    • Supply cabin heat
    • Maintain Catalyst temperature for emissions control
  – Decreased Efficiency
    • Increased friction losses at low temperatures

• Battery System
  – Decreased usable energy capacity
  – Decreased power capability

• Accessories using additional energy
  – Air Conditioner
  – Defroster
Engine Operation is a Main Factor for change of Fuel Economy for PHEV’s

Hymotion Prius Fleet
Percentage of Miles with Engine OFF
(EV Operation)

Percent Miles Engine Off [%] vs Average Ambient Temperature [°C]

-20°C to -10°C
-10°C to 0°C
0°C to 10°C
10°C to 20°C
20°C to 30°C
30°C to 40°C
>40°C

All Trips
CD
CD/CS
CS
Usable Battery Capacity is Slightly Affected by Temperature

Hymotion Prius Battery Energy Capacity
PHEV Fleet Results from Full Charge Trip Sequences

- Discharge Energy
- Usable SOC

Average Ambient Temperature [°C] vs. Usable SOC [%]
NiMH Battery Power Limitation by Prius Calibration

Prius NiMH Pack Max Discharge Power vs. Temperature

Average Ambient Temperature [°C]

Max Discharge Current * Nominal Voltage [kWh]

CD trips
CD/CS trips
CS trips
Li-Ion Battery System Power is also Limited by Prius Calibration at Extreme Temperatures
Incomplete Charging Observed at Very High Temperatures

Hymotion Prius in Phoenix, AZ
High Ambient Temperature Results in Incomplete Charging

![Graph showing the relationship between Max Battery Inlet Air Temperature and Max Battery Cell Temperature for Complete and Incomplete Charge scenarios. The graph indicates that as the Max Battery Inlet Air Temperature increases, the Max Battery Cell Temperature also increases, with a notable trend towards incomplete charge at very high temperatures.]
Hymotion Li-Ion Battery Internal Resistance Change with Temperature

![Graph showing the relationship between Hymotion Pack Voltage and Current across different temperature ranges.](image_url)
Battery Cell Voltage Varies more at Low Temperatures due to Increase Internal Resistance

**Hymotion Prius**
Average Ambient Temperature: 27°C

- Min Cell Voltage
- Max Cell Voltage

**Hymotion Prius**
Average Ambient Temperature: -14°C

- Min Cell Voltage
- Max Cell Voltage
Battery Cells have Moderate Imbalance at Higher Temperatures

Hymotion Prius - Average Ambient Temperature 27°C

Cell Voltage Difference [V]
Battery Power [kW]
Battery Cells have Moderate Imbalance at Mid Temperatures

Hymotion Prius - Average Ambient Temperature: 15C

- Cell Voltage Difference [V]
- Battery Power [kW]
Battery Cells have Increased Imbalance at Low Temperatures

Hymotion Prius - Average Ambient Temperature: -14°C

- Cell Voltage Difference [V]
- Battery Power [kW]
Charging At Low Temperature Requires Increased Energy for Cell Balancing
Charging At Mid Temperature Does Not Require Increased Energy for Cell Balancing
Charging At Higher Temperature Does Not Require Increased Energy for Cell Balancing
Summary

• Extreme ambient temperatures significantly impact PHEV fuel economy
  – Engine operating time increases
  – Accessories utilization increases

• Prius battery control system (calibrated for NiMH) is not able to take full advantage of possible benefits of Li-Ion technology at extreme temperatures

• Battery capabilities show a slight decrease at low temperatures
  – Reduced energy capacity
  – Increased internal resistance
  – Increased cell imbalance which could lead to further reduction in capacity
Acknowledgement

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Additional Information

http://avt.inl.gov
or
http://www1.eere.energy.gov/vehiclesandfuels/avta/
Backup Slides
Prius and Escape Conversion PHEV’s started to emerge in 2006 and are now commercial available.

There have been several announcements of OEM PHEV’s. Ford’s Escape PHEV is available in limited quantities to fleet operations. The Chevy Volt, Chrysler E-Rev and many others are scheduled for production in 2011.

Tesla BEV is currently in limited production. Many announcements from other manufacturers have been made about future production BEV’s.
Engine Operation is a Main Factor for change of Fuel Economy for PHEV’s

Hymotion Prius Fleet - Percentage of Miles with Engine On

<table>
<thead>
<tr>
<th>Average Ambient Temperature [C]</th>
<th>All Trips</th>
<th>CD</th>
<th>CD/CS</th>
<th>CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20C</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>-20C to -10C</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>-10C to 0C</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>0C to 10C</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>10C to 20C</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>20C to 30C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
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<tr>
<td>30C to 40C</td>
<td></td>
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<tr>
<td>&gt;40C</td>
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</tbody>
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Other PHEV Testing

• Bidirectional vehicle-to-grid (V2G) charging study
  – 6 kW and 20 kW levels, using lithium PHEV batteries, V2Green cellular charging control. Documents infrastructure requirements and costs

• City of Seattle \ V2Green lead time-of-day charging demonstration on 13 Seattle-area PHEVs. Includes INL battery impact analysis. Uses wireless charging control

• Developing vehicle-based battery test bed research project for testing PHEV and BEV batteries in various vehicle and charging operating scenarios

• Conduct vehicle \ battery testing on PHEVs when received via DOE’s Technology Assistance and Demonstration Activity
Other PHEV Testing – cont’d

• Tacoma Power charging infrastructure study
  – AVTA and Tacoma Power are collecting data on one section of administration building (800 amp, 480 volt, 3 phase load) and PHEV charging infrastructure
  – Document demand and energy profiles of PHEV charging as portion of facility profiles
  – WiFi local energy meter (LEM) data collection system
PHEV Charging Infrastructure Cost Report

- Analyzes PHEV infrastructure requirements in single and multi-family residential, and commercial facilities as well as driving trends. No site specific costs
- Charging infrastructure equipment/administrative costs:
  - Levels 1 (120V, 15 or 20 amp) and 2 residential
  - Levels 1 and 2 (208/240V ~40 amp) apartment complex
  - Level 2 commercial facility
- Battery sizes & charge times for various PHEV platforms
- Power electronics & battery costs for PHEV platforms

<table>
<thead>
<tr>
<th>Level 1 Residential</th>
<th>Labor</th>
<th>Material</th>
<th>Permits</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVSE (charge cord)</td>
<td>-</td>
<td>$250</td>
<td>-</td>
<td>$250</td>
</tr>
<tr>
<td>Residential circuit installation (20A branch circuit, 120 VAC/1-Phase)</td>
<td>$300</td>
<td>$131</td>
<td>$85</td>
<td>$516</td>
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<tr>
<td>Administration costs</td>
<td>$60</td>
<td>$43</td>
<td>$9</td>
<td>$112</td>
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<tr>
<td>Total Level 1 Cost</td>
<td>$360</td>
<td>$424</td>
<td>$94</td>
<td>$878</td>
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</tbody>
</table>

Report @ http://avt.inl.gov/pdf/phev/phevInfrastructureReport08.pdf